Measurement of the $\Upsilon(nS)$ cross sections in pp collisions at $\sqrt{s} = 7$ TeV

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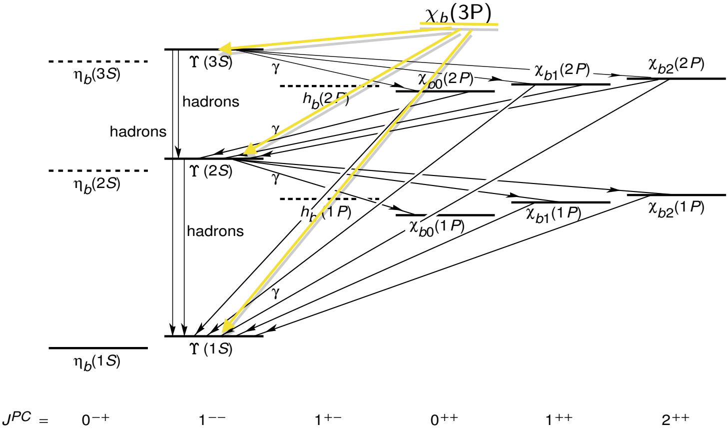
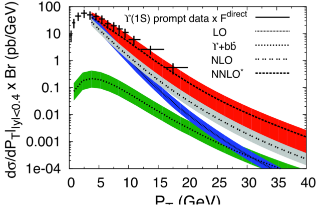
Bottomonium Production

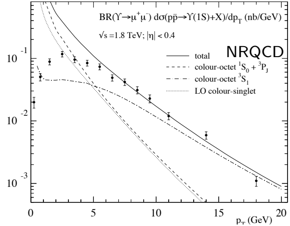
Table: Stages in the hadroproduction of Υ(nS) resonances.

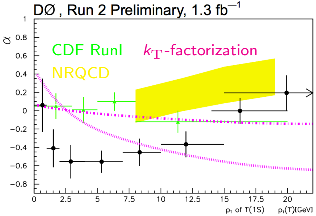
1st step	2nd step	3rd step	production type
$p\bar{p} \to b\bar{b} + X$	$b\bar{b} \to \Upsilon(\mathrm{nS})$	–	prompt, direct
	$b\bar{b} \to \chi_b$	$\chi_b \to \Upsilon(\mathrm{nS}) + \gamma$	prompt, indirect
	$b\bar{b} \to \Upsilon(\mathrm{n'S})$	$\Upsilon(\mathrm{n'S}) \to \Upsilon(\mathrm{nS}) + X$	prompt, indirect

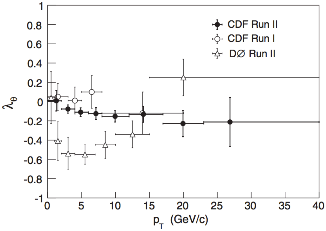


Previous Measurements





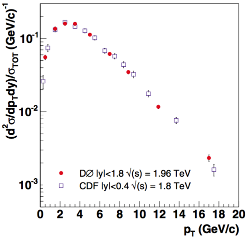


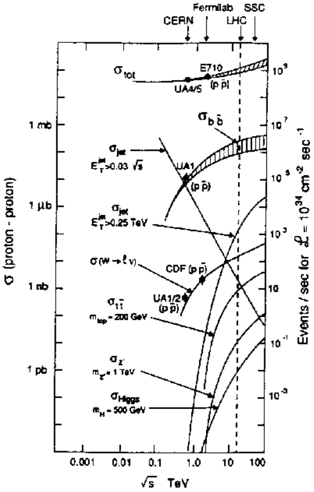


- No theoretical model has simultaneously explained experimental measurements of both production cross section and polarization.
- The polarization measurements from D0 and CDF do not agree with each other.

Study Upsilons at the Large Hadron Collider (LHC)

- LHC provides:
  - New energy scale→Large $\sigma_{b\bar{b}}$
  - Large p_{T} reach can help discriminate between theoretical models
- CMS provides:
  - excellent dimuon mass resolution to separate the Υ(nS) states

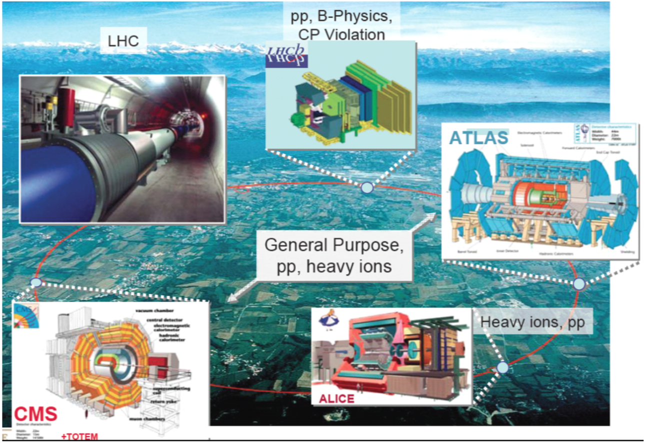




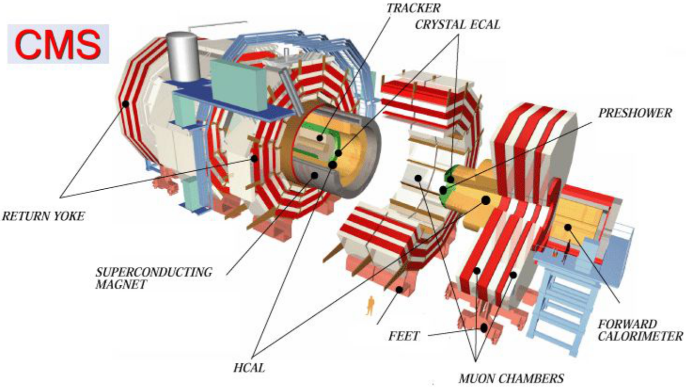
first extension to 50 GeV/c in p_{T} and 2.4 in $|y|$

The LHC

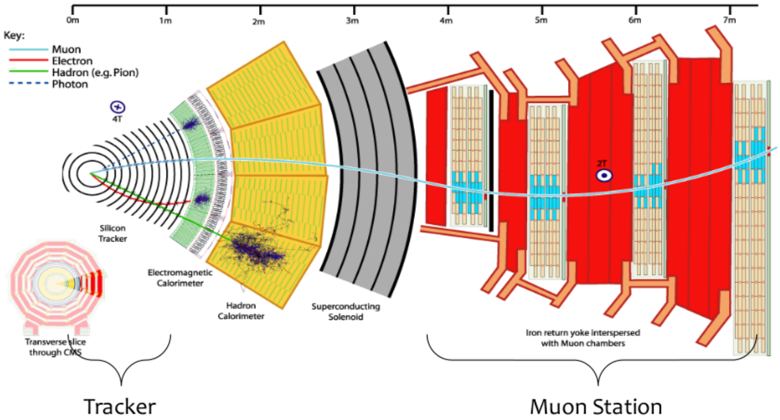
The first collisions at an energy of 3.5 TeV per beam took place on 30th March 2010.



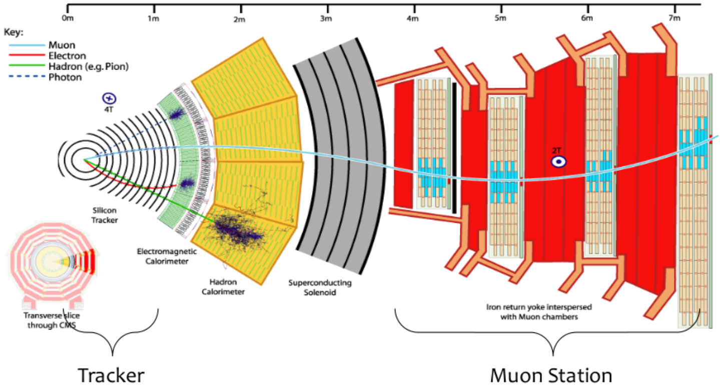
The CMS Detector



Muon Reconstruction



Muon Reconstruction

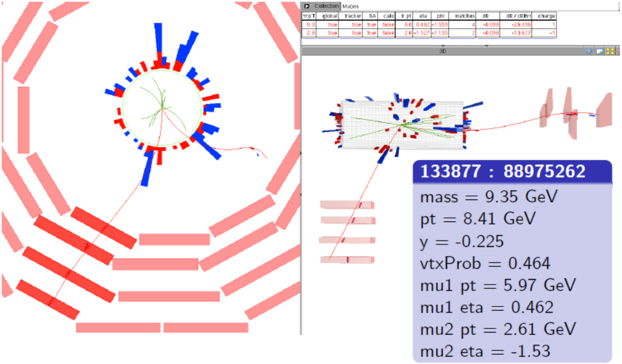


Low p_{T} muons might not transverse more than one instrumented muon layer because of the B-field (mid-rapidity) or material thickness (forward).

Tracker muons were developed to reconstruct muons down to very low momenta, where for identification purposes it is enough to traverse only 1 instrumented muon layer.

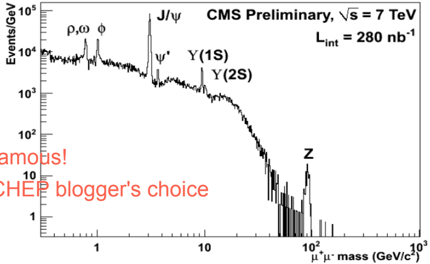
Evolution of the Analysis

- Monte Carlo Feasibility Study in 2008. First analysis note came out in 2009, CMS AN-2009/118
- Early 2010, the first Υ candidate was detected and was shown for the first time to the public by Yu in the International Workshop on Heavy Quarkonium 2010.

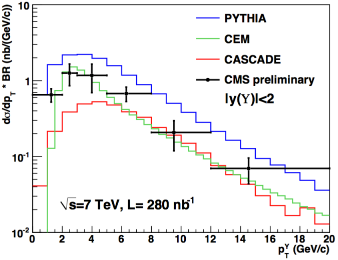


Evolution of the Analysis

- July 2010, the first Υ cross section measurement result was shown to public at ICHEP. ($280\ \mathrm{nb}^{-1}$)



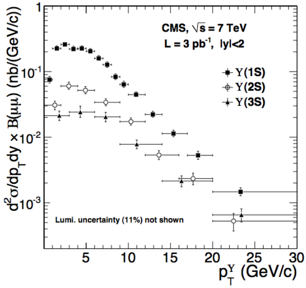
Famous!
ICHEP blogger's choice

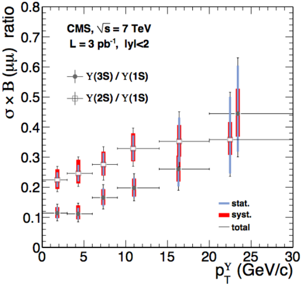


Yu's contribution: data skimming; event selection cuts; efficiency measurements in data and MC

Evolution of the Analysis

- Analysis using 3 pb^{-1} data collected in 2010 was published in PRD
- The first CMS result published in PRD
- The first Υ(nS) measurement at the LHC
  - Yu's contributions for the first publication were similar to the 280/nb analysis





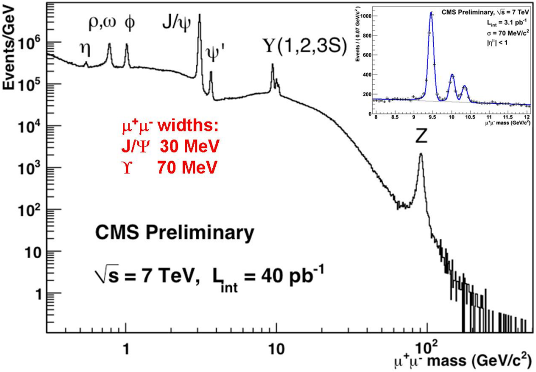
- Since 2011, we started to extend this measurement with a larger ($\times$10) dataset.
  - Yu is in charge of the full analysis.

Outline

- Datasets and Selection
- Measurement Methodology
- Analysis Ingredients
- Results, fiducial and acceptance-corrected cross section
- Discussions and Comparisons

Datasets

- data collected in 2010, the first 3 pb^{-1} was not included:
  /MuOnia/Run2010B-Nov4ReReco_v1/RECO 36/pb

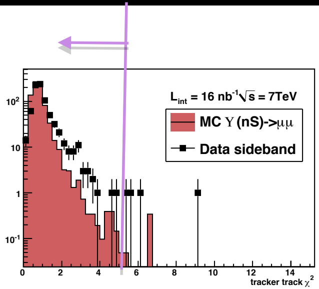


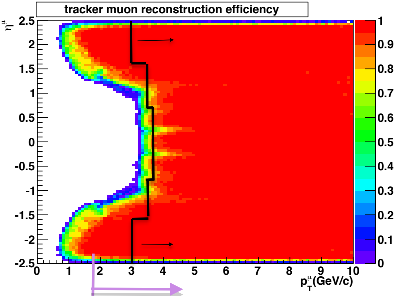
Trigger (Online Selection)

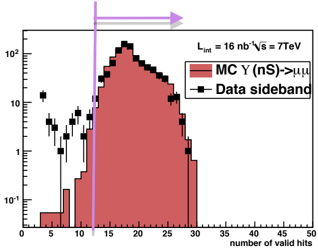
The CMS trigger system performs the online event selection in two steps:

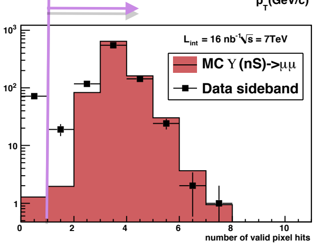
- L1:
  - hardware-based, fast and automatic, look for simple signs of interesting physics
  - uses only coarsely segmented data from all the three muon systems
- HLT:
  - software-based, is capable of complex calculations
  - two levels:
    - L2: takes L1 candidates as seeds to perform a stand alone reconstruction
    - L3: takes L2 candidates as seeds and adds information from tracker
- Trigger used in this analysis:
  - HLT_DoubleMu0 (run 146428 to 147116): requires the detection of two muons without an explicit p_T^{μ} requirement.
  - HLT_DoubleMu0_Quarkonium_v1 (since run 147196): HLT_DoubleMu0 + dimuon with opposite charge, $1.5 < M_{\mu\mu} < 14.5$

Offline Selection Cuts









Choice of criteria: Signal MC, background from data sidebands, Maximizing $S/\sqrt{(S+B)}$

Offline Selection

Di-Muon:

- opposite charge
- vertex chi2 probability > 0.001
- $|y| < 2.4$ ($y = \frac{1}{2} ln(\frac{E+p_z c}{E-p_z c})$)
- dz < 2.0 (The longitudinal separation between the two muons along the beam axis)

Each Muon:

- Fiducial Cuts: $p_T > 3.75 GeV/c$ when $|\eta| < 0.8$, $p_T > 3.5 GeV/c$ when $0.8 < |\eta| < 1.6$, $p_T > 3.0 GeV/c$ when $1.6 < |\eta| < 2.4$ ($\eta = -ln[tan(\frac{\theta}{2})]$)
- is tracker muon
- track quality cuts:
  - innerTrack.numberOfValidHits $>$11
  - innerTrack.hitPattern.pixelLayersWithMeasurement > 0
  - innerTrack.normalizedChi2 < 5
- impact parameter cuts:
  - innerTrack.$|dz| < 25$ (longitudinal)
  - dB < 0.2 (transverse)

If multiple candidates are found, choose the one with largest vertex chi2 probability.

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Cross Section Measurement

The $\Upsilon(nS)$ cross sections are measured and will be presented in the following ways:

- Fiducial cross section
  - defined within the fiducial region
  - not corrected for acceptance, thus not affected by polarization
- Cross section
  - acceptance corrected
  - polarization effect not included in systematics, but quote different cross sections for discrete polarization values
- Cross section utilizing polarization values measured with CMS
  - polarization treated as systematic
  - limited to the polarization measurement fiducial region

The Ingredients to Determine the Cross Section

$$\frac{d\sigma\left(pp \to \Upsilon(\mathrm{nS})X\right)}{dp_T\,dy}\,\mathcal{B}\left(\Upsilon(\mathrm{nS}) \to \mu^+\mu^-\right) = \frac{N^{\mathrm{fit}}_{\Upsilon(\mathrm{nS})}(p_T; \mathcal{A}, \epsilon_{\mathrm{track}}, \epsilon_{\mathrm{id}}, \epsilon_{\mathrm{trig}})}{\mathcal{L}\ \cdot \Delta p_T \cdot \Delta y}\,, \quad (1)$$

- $\mathcal{B}\left(\Upsilon(\mathrm{nS}) \to \mu^+\mu^-\right)$: Branching fraction of $\Upsilon(\mathrm{nS}) \to \mu^+\mu^-$
- $\mathcal{A}$: Geometric acceptance, obtained in Monte Carlo (NOT USED IN PRODUCING FIDUCIAL CROSS SECTION RESULTS)
- $\epsilon = \epsilon_{\mathrm{track}} \cdot \epsilon_{\mathrm{id}} \cdot \epsilon_{\mathrm{trig}}$
  - $\epsilon_{\mathrm{track}}$: Tracking efficiency, determined with a track-embedding technique
  - $\epsilon_{\mathrm{id}}, \epsilon_{\mathrm{trig}}$: Muon identification and trigger efficiency, determined with the tag-and-probe technique
- $N_{\Upsilon(\mathrm{nS})}$: The $\Upsilon(\mathrm{nS})$ yields, extracted via an extended unbinned maximum likelihood fit
- $\mathcal{L}$: The integrated luminosity of the dataset, $35.8 \pm 1.4\ pb^{-1}$

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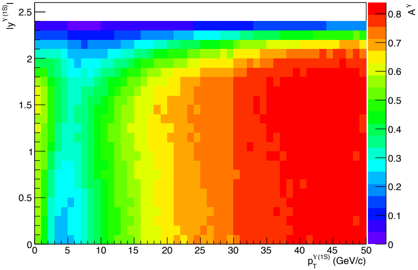
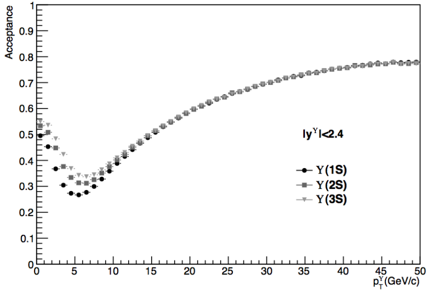
Acceptance ($\mathcal{A}$)

$$\mathcal{A}\left(p_T^{\Upsilon}, y^{\Upsilon}\right) = \frac{N^{\mathrm{reco}}\left(p_T^{\Upsilon}, y^{\Upsilon} \middle| \text{SiTRK track pair satisfies fiducial cuts}\right)}{N^{\mathrm{gen}}\left(p'^{\Upsilon}_T, y'^{\Upsilon}\right)}, \tag{2}$$

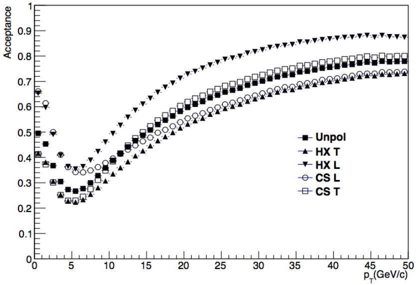
- Geometric and kinematic
- High-Statistics MC Υ(nS) Gun samples, generated flat in Υp_T
- Different acceptance maps for 1S, 2S and 3S





Acceptance vs. Polarization

- Acceptance is a strong function of production polarization
- Acceptance is not used in fiducial cross section results
- Following the 3 pb^{-1} analysis, for the acceptance-corrected production cross section results, quote different cross sections for discrete polarization values



HX: the helicity frame, where the polar axis coincides with the direction of the Υ momentum;
CS: the Collins-Soper frame whose axis is the average of the two beam directions in the Υ rest frame
T : fully transversely polarized
L : fully longitudinally polarized

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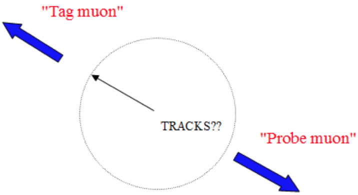
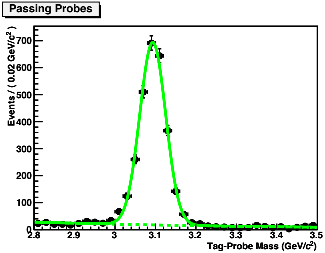
Tag and Probe Methodology for Efficiencies (ϵ)

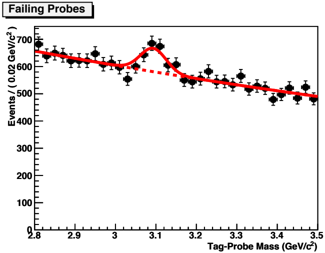
- Data driven technique, efficiencies measured with data
- Use J/Ψ resonance given the higher statistics
- Tag: Well-identified, good track quality, passes muon leg of Mu+track J/Ψ trigger
- Probe:
  - ID: Tracks with good quality
  - Trigger: Tracker muon
- Passing Probes:
  - ID: is Tracker muon
  - Trigger: pass desired trigger
- Tag-Probe pair:
  - $2.6 < mass < 3.5$
  - $\Delta R > 0.6$: remove close-by muons

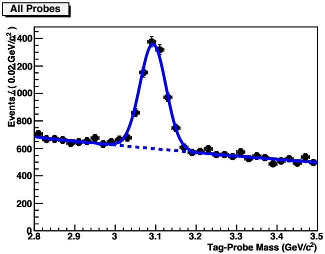


Tag and Probe Example

- Example in one p_{T} and $|\eta|$ bin: Muon ID, $p_T^{\mu}(3.5,3.75)$, $\eta^{\mu}(0.8,1.2)$ There are 72 for each efficiency in the analysis.



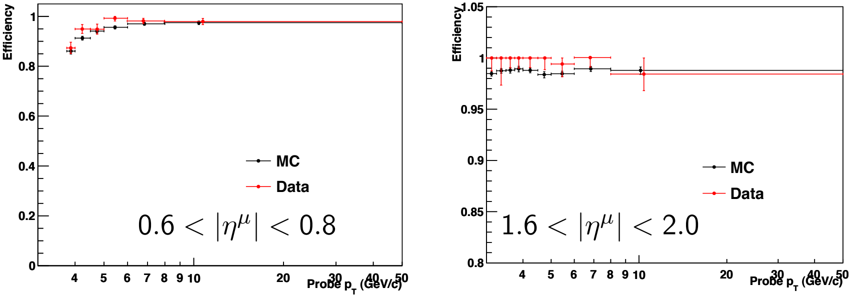




efficiency = 0.89 ± 0.02
lf = -0.419 ± 0.04
lp = -1.59 ± 0.2
mean = 3.0933 ± 0.0007
numBackgroundFail = 19933 ± 155
numBackgroundPass = 592 ± 30
numSignalAll = 3056 ± 86
sigma = 0.0320 ± 0.0006

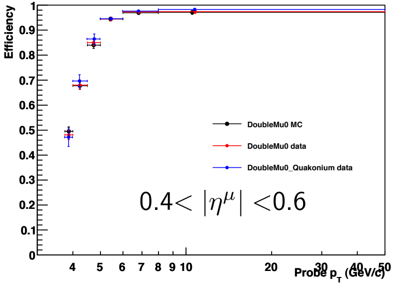
MuonID Efficiencies (ϵ_{id})

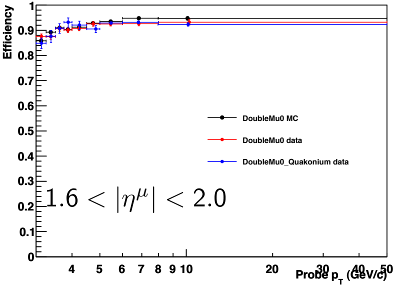
- measured in 8 η^{μ} bins and 9 p_T^{μ} bins



Trigger Efficiencies (ϵ_{trig})

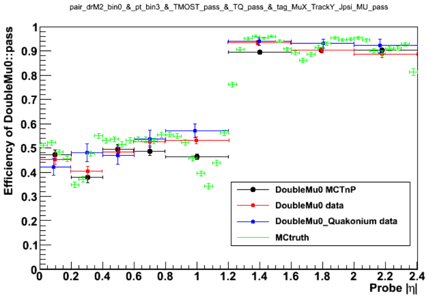
black: DoubleMu0, Data;
blue: DoubleMu0_Quarkonium_v1, Data;
red: DoubleMu0, MC

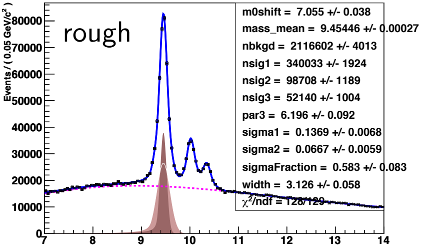


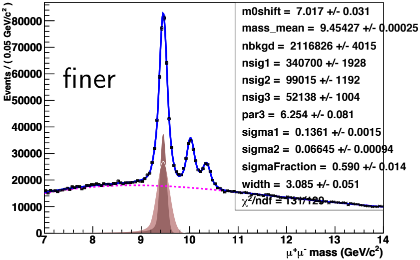


η Dependence of Efficiencies

- Both trigger and ID efficiencies show $|\eta|$ dependence, especially in low p_T region
- The inefficiencies at $|\eta| = 0.2, 1.1, 1.7$ are due to the detector geometry
- The MC truth efficiencies are measured in rough (same as for data) and finer η binnings. Apply the efficiencies to the cross section measurement, we observe negligible differences.





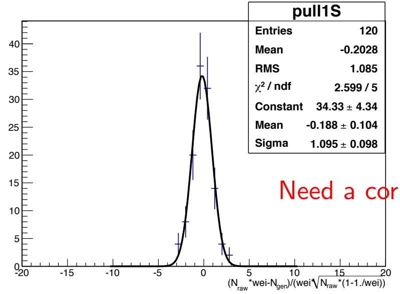


The difference in 1S yield: 2 per mill

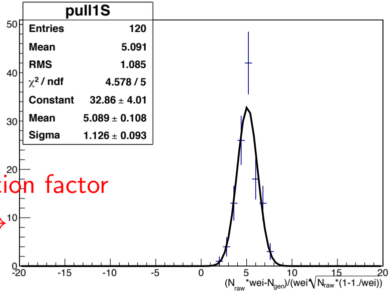
Monte Carlo Closure Test

- Divide Fall10 MC sample into 120 $1pb^{-1}$ samples and perform a full analysis on each sample.
- Add offline selections one by one. At each step we quantify the agreement between measurements and MC truth using the pull distribution

Acceptance, Tracking, Track Quality, MC truth Dimuon(Υ) efficiencies



Acceptance, Tracking, Track Quality, Single Muon TnP Efficiencies Product (use MC J/Ψ sample)



Need a correction factor

- A pull less than 2 sigma away from unity
- All the ingredient inputs are correct

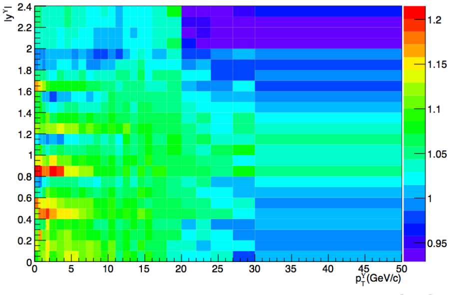
- A biased pull, with a shifted mean at 5.1
- The single muon TnP efficiencies product measured with MC J/Ψ sample show a bias

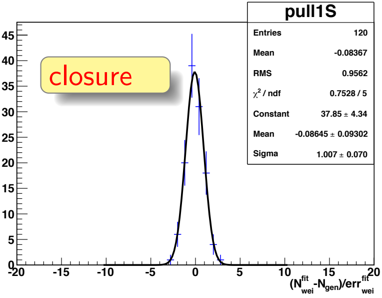
Correction Factor (ρ)

The ρ factor is defined as:

$$\epsilon(\Upsilon) = \epsilon(\mu^{1}_{J/\Psi}) \cdot \epsilon(\mu^{2}_{J/\Psi}) \cdot \rho \qquad (3)$$

- $\epsilon(\Upsilon)$: Monte Carlo Truth Matching Dimuon (Υ) Efficiency
- $\epsilon(\mu^{i}_{J/\Psi})$: Monte Carlo Tag and Probe Single Muon Efficiency measured with J/Ψ
- A correction to the factorization hypothesis
- Accounts for the bias introduced by the Tag and Probe efficiency measurement with J/Ψ





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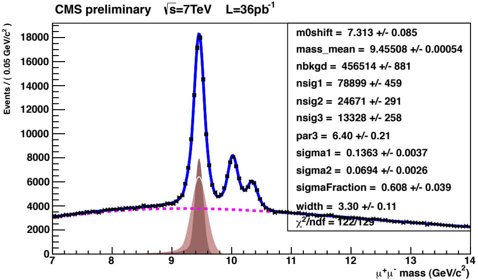
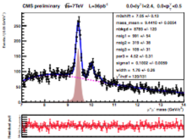
Mass Fits($N_{\Upsilon(\mathrm{nS})}$)

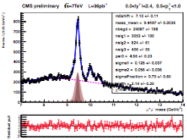


- Signal Pdf: Double Crystal Ball (Gaussian core portion and a power-law low-end tail) for high statistics p_T bins and Single Crystal Ball for rather low statistics p_T bins (typically with 1S yield fewer than 1000)
- Background Pdf: error function times exponential; error function not used when exponential is enough
- Mass differences fixed to precise PDG values
- Common width parameters scaled by the mass
- Crystal Ball radiative tail parameter fixed from high stats MC

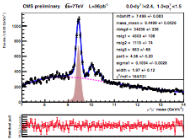
Mass Fits (low p_T bins)



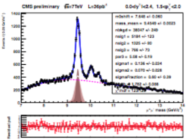
(a) $0.0 < p_T < 0.5$



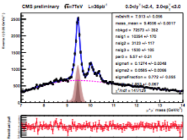
(b) $0.5 < p_T < 1.0$



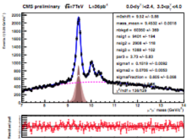
(c) $1.0 < p_T < 1.5$



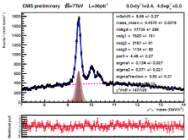
(d) $1.5 < p_T < 2.0$



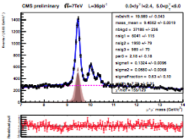
(e) $2.0 < p_T < 3.0$



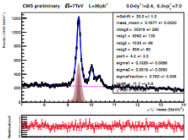
(f) $3.0 < p_T < 4.0$



(g) $4.0 < p_T < 5.0$



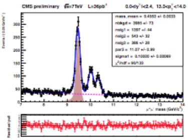
(h) $5.0 < p_T < 6.0$



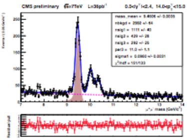
(i) $6.0 < p_T < 7.0$

signal: double CB
background: exponential and error function product

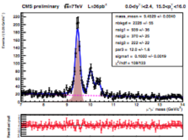
Mass Fits (high p_T bins)



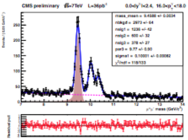
(d) $13.0 < p_T < 14.0$



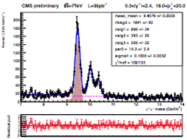
(e) $14.0 < p_T < 15.0$



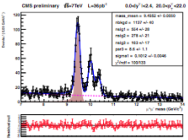
(f) $15.0 < p_T < 16.0$



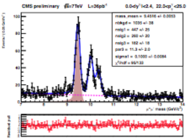
(g) $16.0 < p_T < 18.0$



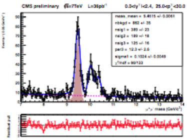
(h) $18.0 < p_T < 20.0$



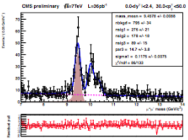
(i) $20.0 < p_T < 22.0$



(j) $22.0 < p_T < 25.0$



(k) $25.0 < p_T < 30.0$



(l) $30.0 < p_T < 50.0$

signal: single CB
background: exponential

Candidate Weighting

- p_T and η of each muon determines the reconstructability of a Υ
- incorporate acceptance and efficiency for each muon in yield extraction
- Via: per candidate weighting

$$\mathrm{w} \equiv \mathrm{w_{acc}} \cdot \mathrm{w_{track}} \cdot \mathrm{w_{id}} \cdot \mathrm{w_{trig}} \cdot \mathrm{w_{misc}} \cdot \mathrm{w}_\rho \quad (4)$$

$$\mathrm{w_{acc}} = 1/\mathrm{A}^{\Upsilon}(p_T, \mathrm{y}) \quad (5)$$

$$\mathrm{w_{track}} = 1/\epsilon^2_{track} \quad (6)$$

$$\mathrm{w_i} = 1/[\epsilon_i(p_T^{\mu_1}, \eta^{\mu_1}) \cdot \epsilon_i(p_T^{\mu_2}, \eta^{\mu_2})] \quad (7)$$

$$\mathrm{w}_\rho = 1/\rho^{\Upsilon}(p_T, \mathrm{y}) \quad (8)$$

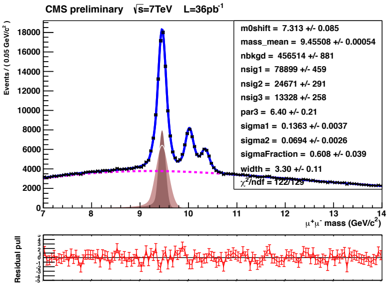
for i = id, trig

Additional selection criteria, $\mathrm{w_{misc}}$, including the efficiency of the vertex selection criteria.

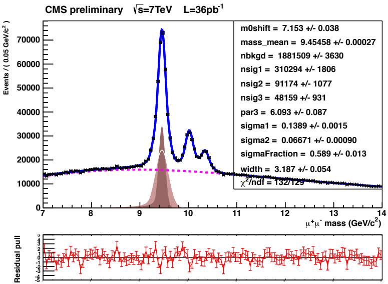
- Fit the mass spectrum after weighting in each p_T or $|y|$ interval to extract the weighted yield.

Candidate Weighting (Examples)

Raw Yield



Weighted Yield



average all-eff: 0.29 acc: 0.40 trg: 0.75 muid: 0.96 trk: 1.00 rho: 1.07

average all-wei: 4.10 wacc: 2.81 wtrg: 1.43 wmuid: 1.04 wtrk: 1.00 wrho: 0.94

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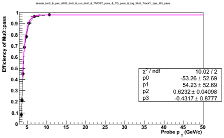
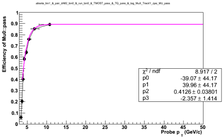
- Efficiencies
  Vary weights coherently by $\pm$ 1σ for each efficiency and sum in quadrature (id: 2-4%, trig: 1-6%) (dominant uncertainty)
- ρ factor
  Repeat the measurements with unit ρ factors. (2-9%) (dominant)
- M_{scale}
  The mismeasurement of the track momentum shifts and broadens the reconstructed peaks of dimuon resonances. Varying the correction parameters by $\pm 1\sigma$(stat.) (0.1-1%)
- PDF
  - Signal: Vary one of the CB tail parameters and redo the fits. (1-2%)
  - Background: Vary the background PDF with polynomial in a restricted mass region (8,12). (1-4%)
- Luminosity (4%)

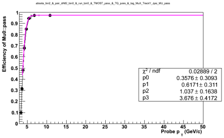
- <u>Bin choice of efficiencies</u>
  Fit the 1D efficiency as a function of p_T using a hyperbolic tangent function (1-3%)



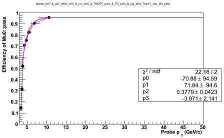
(a) $|\eta^\mu| < 0.2$



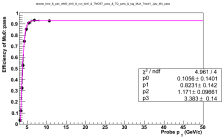
(b) $0.2 < |\eta^\mu| < 0.4$



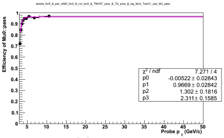
(c) $0.4 < |\eta^\mu| < 0.6$



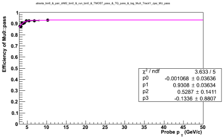
(d) $0.6 < |\eta^\mu| < 0.8$

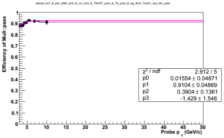


(e) $0.8 < |\eta^\mu| < 1.2$

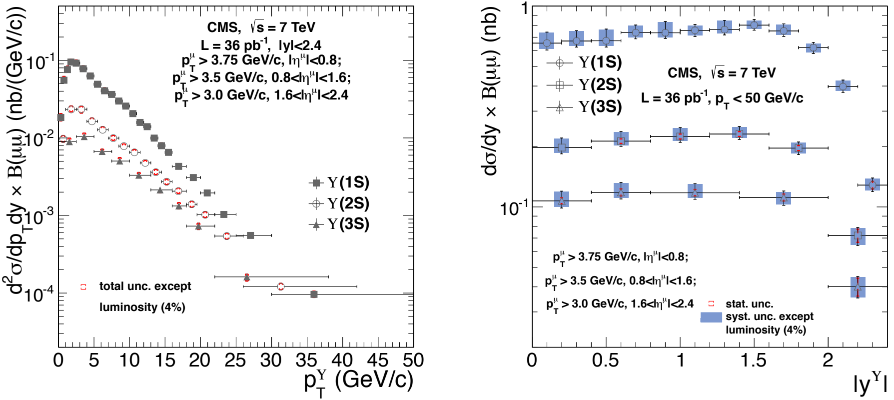


(f) $1.2 < |\eta^\mu| < 1.6$





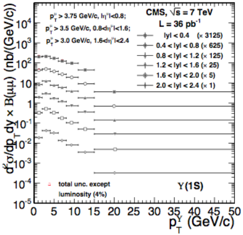
Results: Differential Fiducial X-section vs. p_T and $|y|$



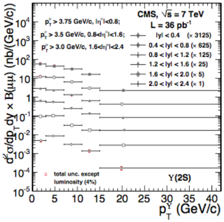
- The $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ p_T differential x-sections are measured in twenty-five, sixteen and nine bins respectively.
- The $\Upsilon(nS)$ $|y|$ differential x-sections drop significantly at high $|y|$

Results: Differential Fiducial X-section vs p_T, in different $|y|$ regions

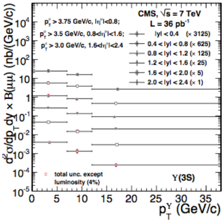
- The p_T differential x-sections of Υ(nS) are measured in different $|y|$ bins: (0,0.4), (0.4,0.8), (0.8,1.2), (1.2,1.6), (1.6,2.0), (2.0,2.4)
- Similar trends in all $|y|$ bins



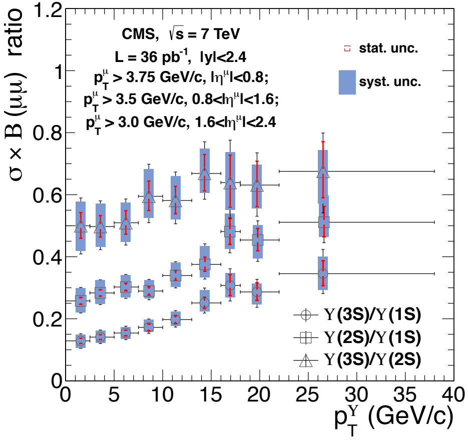
(a) $\Upsilon(1S)$



(b) $\Upsilon(2S)$



(c) $\Upsilon(3S)$



- All the ratios in the plot ascend when p_T goes up.

Results of the Fiducial Cross Section

$$\frac{d\sigma\,(pp \to \Upsilon(\mathrm{nS})X)}{dp_T\,dy}\,\mathcal{B}\left(\Upsilon(\mathrm{nS}) \to \mu^+\mu^-\right) = \frac{N^{\mathrm{fit}}_{\Upsilon(\mathrm{nS})}(p_T;\epsilon_{\mathrm{track}},\epsilon_{\mathrm{id}},\epsilon_{\mathrm{trig}})}{\mathcal{L}\ \cdot \Delta p_T \Delta y}\,, \quad (9)$$

Integrated over $|y| < 2.4$, the total Υ(nS) fiducial cross-section within the cuts $\mathrm{p}_{\mathrm{T}}^{\mu} > 3.75\ \mathrm{GeV/c}$ for $|\eta|^{\mu} < 0.8$, $\mathrm{p}_{\mathrm{T}}^{\mu} > 3.5\ \mathrm{GeV/c}$ for $0.8 < |\eta|^{\mu} < 1.6$ and $\mathrm{p}_{\mathrm{T}}^{\mu} > 3.0\ \mathrm{GeV/c}$ for $1.6 < |\eta|^{\mu} < 2.4$ on both muons are:

$$\sigma(pp \to \Upsilon(1\mathrm{S})X) \cdot \mathcal{B}(\Upsilon(1\mathrm{S}) \to \mu^+\mu^-) = (3.06 \pm 0.02^{+0.27}_{-0.25} \pm 0.12)\ \mathrm{nb}\,,$$

$$\sigma(pp \to \Upsilon(2\mathrm{S})X) \cdot \mathcal{B}(\Upsilon(2\mathrm{S}) \to \mu^+\mu^-) = (0.91 \pm 0.01^{+0.08}_{-0.07} \pm 0.04)\ \mathrm{nb}\,,$$

$$\sigma(pp \to \Upsilon(3\mathrm{S})X) \cdot \mathcal{B}(\Upsilon(3\mathrm{S}) \to \mu^+\mu^-) = (0.49 \pm 0.01^{+0.04}_{-0.04} \pm 0.02)\ \mathrm{nb}\,,$$

mean $\pm$ statistical $\pm$ systematic $\pm$ Lumi

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Evaluation of Systematic Uncertainties for the Acceptance-corrected Cross Section

The difference between the fiducial and the acceptance-corrected cross section are the acceptance corrections.

Besides those that have been already explained in the previous slides, the following acceptance related systematics are also included here:

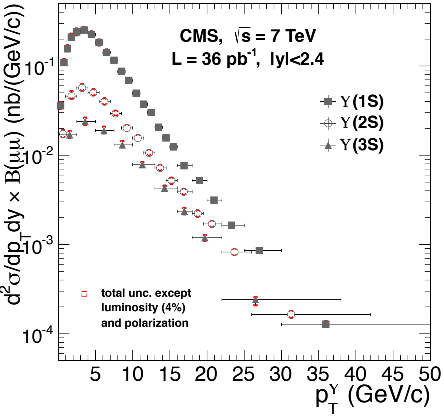
- Acceptance
  Vary weights coherently by $\pm 1\sigma$ for acceptance (0.3-1%)
- FSR
  Remove events with photons from Υ and recompute the acceptance. (0.1-0.8%)
- Momentum Scale
  Acceptance is based on reconstructed p_{T}. Vary the p_{T} resolution by $\pm 10\%$ and recompute the acceptance maps. (0.1-0.2%)
- p_{T} spectrum
  Acceptance is measured with Υ Gun sample with a flat p_{T} spectrum. Reweight it with the p_{T} spectrum from PYTHIA. (0.1-0.7%)

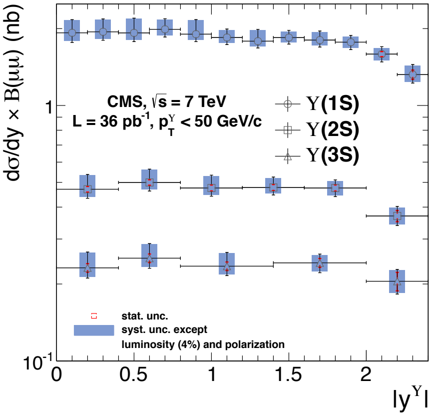
Systematic Uncertainties

Table: Relative values of systematic uncertainties on the Υ(nS) production integrated over the rapidity range $|y^{\Upsilon}| < 2.4$, times the dimuon branching fraction, in units of percent.

	p_{T} (GeV/c)	A	$\epsilon_{\mathrm{T\&P}}$	ϵ_{ρ}	PDF	other
Υ(1S)	0.0 – 50.0	1.0 (1.0)	4.6 (4.0)	6.8	1.8	0.4(0.3)
Υ(2S)	0.0 – 42.0	1.1 (1.1)	5.0 (4.3)	7.4	2.6	0.4(0.4)
Υ(3S)	0.0 – 38.0	1.2 (1.1)	4.7 (3.9)	8.0	3.8	0.6(0.5)

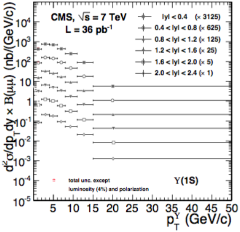
Results: Differential $\Upsilon(nS)$ Production X-section vs. p_T and $|y|$



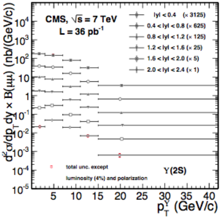


- The $\Upsilon(nS)$ $|y|$ differential x-sections decreases at large $|y|$, but not as significantly as in the fiducial cross section.

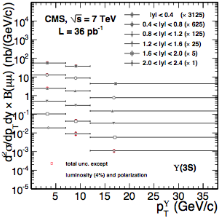
- The p_T differential x-sections of Υ(nS) are measured in different $|y|$ bins: (0,0.4), (0.4,0.8), (0.8,1.2), (1.2,1.6), (1.6,2.0), (2.0,2.4)
- Similar trends in all $|y|$ bins



(a) Υ(1S)



(b) Υ(2S)



(c) Υ(3S)

Results: Total Production Cross Section

$$\frac{d\sigma\,(pp \to \Upsilon(\mathrm{nS})X)}{dp_T dy}\,\mathcal{B}\left(\Upsilon(\mathrm{nS}) \to \mu^+\mu^-\right) = \frac{N^{\mathrm{fit}}_{\Upsilon(\mathrm{nS})}(p_T; \mathcal{A}, \epsilon_{\mathrm{track}}, \epsilon_{\mathrm{id}}, \epsilon_{\mathrm{trig}})}{\mathcal{L}\ \cdot \Delta p_T \Delta y}\,, \tag{10}$$

The Υ(nS) integrated production cross sections (sum of differential x-sections), for $|y| < 2.4$:

$$\sigma(pp \to \Upsilon(1\mathrm{S})X) \cdot \mathcal{B}(\Upsilon(1\mathrm{S}) \to \mu^+\mu^-) = (8.55 \pm 0.05^{+0.74}_{-0.71} \pm 0.34)\ \mathrm{nb}\,,$$

$$\sigma(pp \to \Upsilon(2\mathrm{S})X) \cdot \mathcal{B}(\Upsilon(2\mathrm{S}) \to \mu^+\mu^-) = (2.21 \pm 0.03^{+0.21}_{-0.20} \pm 0.09)\ \mathrm{nb}\,,$$

$$\sigma(pp \to \Upsilon(3\mathrm{S})X) \cdot \mathcal{B}(\Upsilon(3\mathrm{S}) \to \mu^+\mu^-) = (1.11 \pm 0.02^{+0.12}_{-0.11} \pm 0.04)\ \mathrm{nb}\,,$$

mean $\pm$ statistical $\pm$ systematic $\pm$ Lumi

quote different cross sections for discrete polarization values:

	p_T (GeV/c)	HX T	HX L	CS T	CS L	HX$\frac{1}{2}$T	HX$\frac{1}{2}$L	CS$\frac{1}{2}$T	CS$\frac{1}{2}$L	HX$\frac{1}{4}$T	HX$\frac{1}{4}$L	CS$\frac{1}{4}$T	CS$\frac{1}{4}$L
Υ(1S)	0.0 − 50.0	+19	−24	+16	−19	+10	−11	+8	−9	+5	−5	+4	−5
Υ(2S)	0.0 − 42.0	+14	−24	+13	−20	+5	−12	+6	−10	+3	−7	+2	−6
Υ(3S)	0.0 − 38.0	+16	−21	+14	−17	+9	−9	+8	−7	+5	−4	+5	−3

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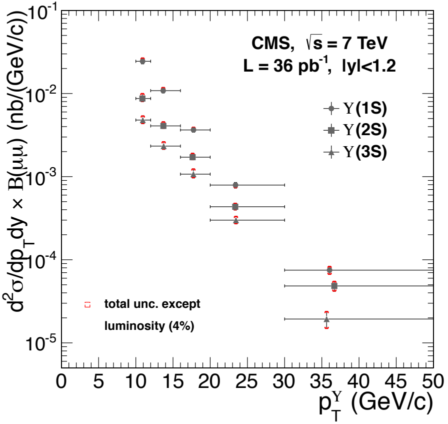
Results utilizing the polarization results from CMS

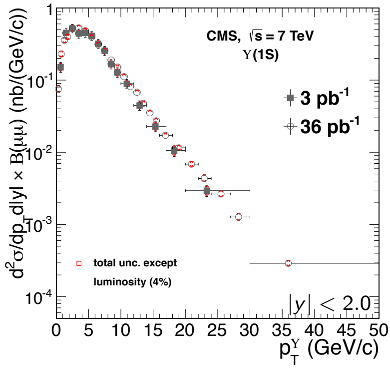


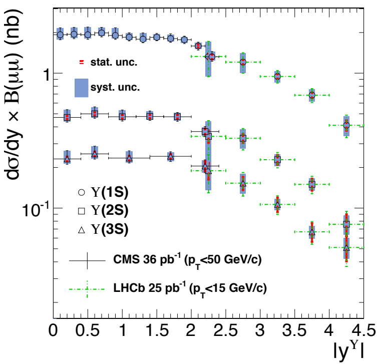
- The polarization measurement from CMS became public recently (arXiv:1209.2922)
- Measured for $10 < p_{\mathrm{T}}^{\Upsilon} < 50$ and $|y^{\Upsilon}| < 1.2$
- Acceptances are calculated using the polarization results

	σ	$\frac{\text{stat.}}{\sigma}$	$\frac{\sum_{\text{syst.}}}{\sigma}$	$\frac{\text{pol.}}{\sigma}$	$\frac{\Delta\sigma}{\sigma}$
$\Upsilon(1\mathrm{S})$	0.56	1.3	9 (8)	4 (2)	11 (9)
$\Upsilon(2\mathrm{S})$	0.21	2.4	7 (8)	7 (3)	11 (9)
$\Upsilon(3\mathrm{S})$	0.13	3.2	9 (8)	7 (3)	12 (9)

Outline

Discussion of the Results

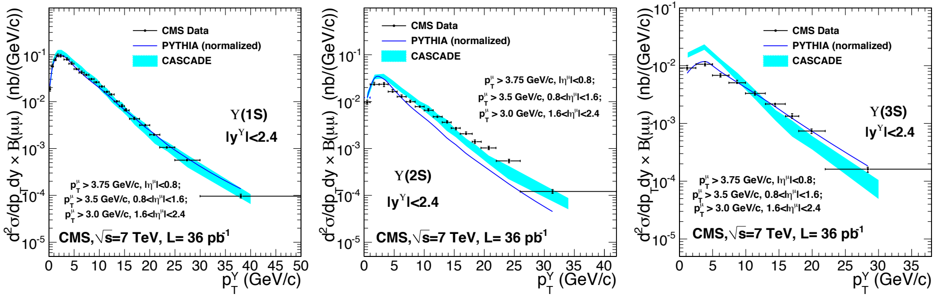




- Recompute the production x-section results for $|y| < 2.0$ in order to compare with previous $3\ \mathrm{pb}^{-1}$ results
- Show good agreement

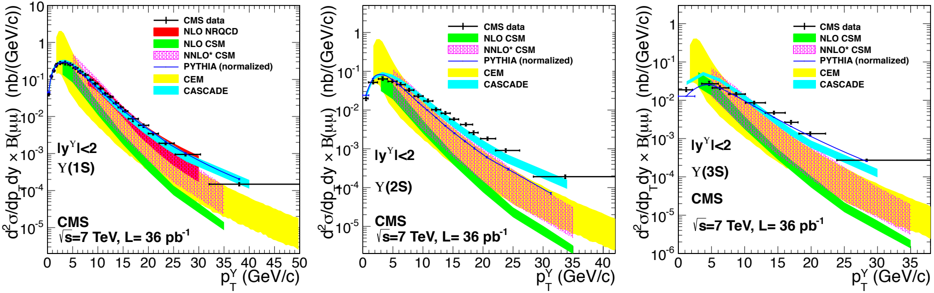
- Compare rapidity-differential acceptance-corrected cross section with LHCb results
- Show good agreement
- Cross section decreases for high $|y|$ values

Theory Comparison, p_T differential fiducial cross sections



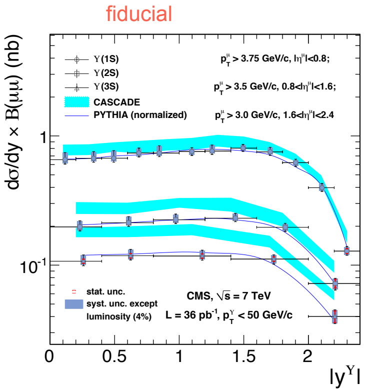
- PYTHIA describes $\Upsilon(1S)$ and $\Upsilon(3S)$ shapes reasonably well.

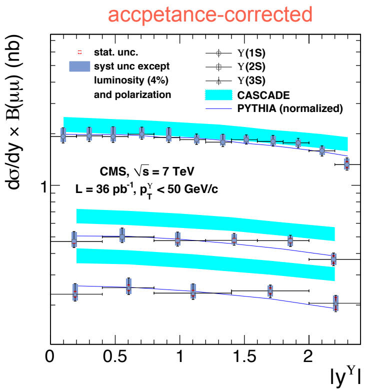
Theory Comparison, p_{T} differential acceptance-corrected cross sections



- NRQCD describes well the $\Upsilon(1S)$ measurement in higher p_{T} region.
- CASCADE describes well the $\Upsilon(1S)$ measurement in the whole region but not the $\Upsilon(2S)$ or $\Upsilon(3S)$.
- PYTHIA has been normalized, it overestimates the total cross section by a factor of 2; it can describe $\Upsilon(1S)$ and $\Upsilon(3S)$ shape but not the $\Upsilon(2S)$.

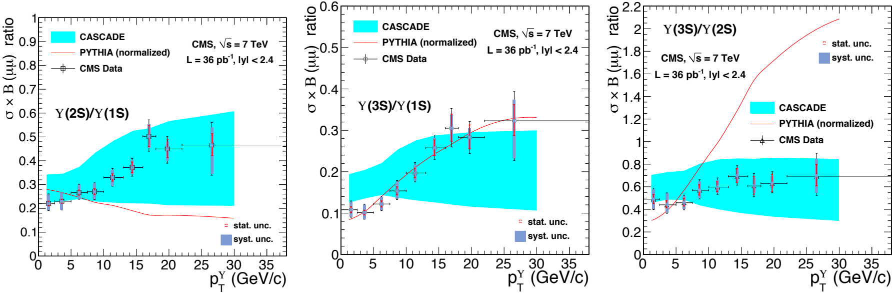
Theory Comparison, $|y|$ differential cross sections





- PYTHIA (normalized) describes the Υ(nS) shapes very well.
- CASCADE agrees with the Υ(1S) but predicts larger total cross sections for the 2S and 3S.

Theory Comparison, cross section ratios



- PYTHIA (normalized) cannot account for the $\Upsilon(2S)/\Upsilon(1S)$ and $\Upsilon(3S)/\Upsilon(2S)$ ratio due to its inability to describe the $\Upsilon(2S)$ cross section.
- The CASCADE prediction is consistent with the $\Upsilon(2S)/\Upsilon(1S)$ and $\Upsilon(3S)/\Upsilon(2S)$ ratios while it does not describe the $\Upsilon(3S)/\Upsilon(1S)$ ratio at low p_{T}.

Summary

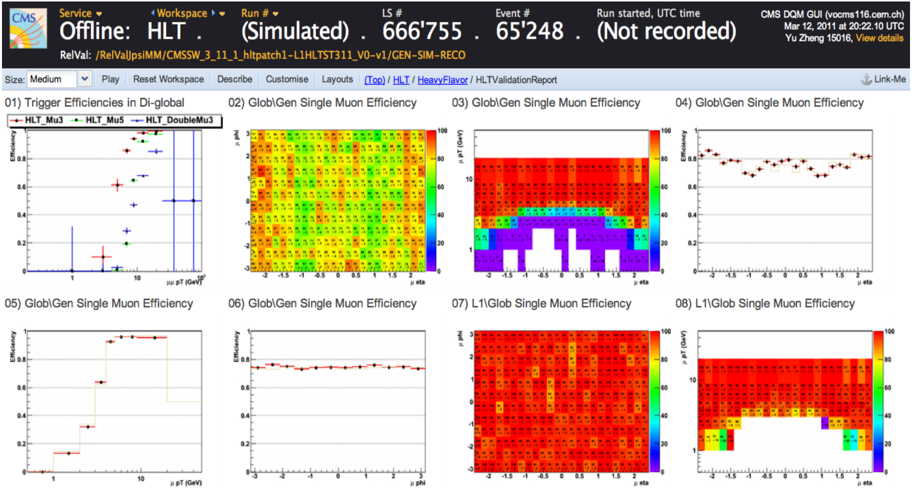
- The Υ(nS) cross sections with and without acceptance corrections have been measured.
- A Monte Carlo closure test has been performed to validate the analysis strategy.
- The p_{T} and $|y|$ differential cross sections and the ratios of cross sections have been shown.
- The systematic uncertainties and effects from polarization have been estimated. The dominant systematic is from the uncertainty in the efficiencies.
- The results have been compared to the results from other experiments and various theoretical models.

A List of Analyses Contributed

- **Υ Cross Section Measurement in pp collisions at $\sqrt{s}$=7 TeV (36 pb^{-1})** *BPH-11-001, under collaboration review*
- **Υ Cross Section Measurement in pp collisions at $\sqrt{s}$=7 TeV (3 pb^{-1})** *Phys.Rev.D83:112004,2011*
- **Search in leptonic channels for heavy resonances decaying to long-lived neutral particles** *submitted to JHEP*
- **Observation of sequential Upsilon suppression in PbPb collisions** *Accepted by PRL*
- **Suppression of Υ excited states in PbPb collisions** *PhysRevLett.107.052302*
- **Feasibility Study of Searching for Long-Lived Parents of the Z^0 Boson at the CMS** *winning poster in the 1st USLUO meeting*
- **Feasibility Study of Prompt J/Ψ Cross Section Measurement at the CMS** *APS talk 2009*

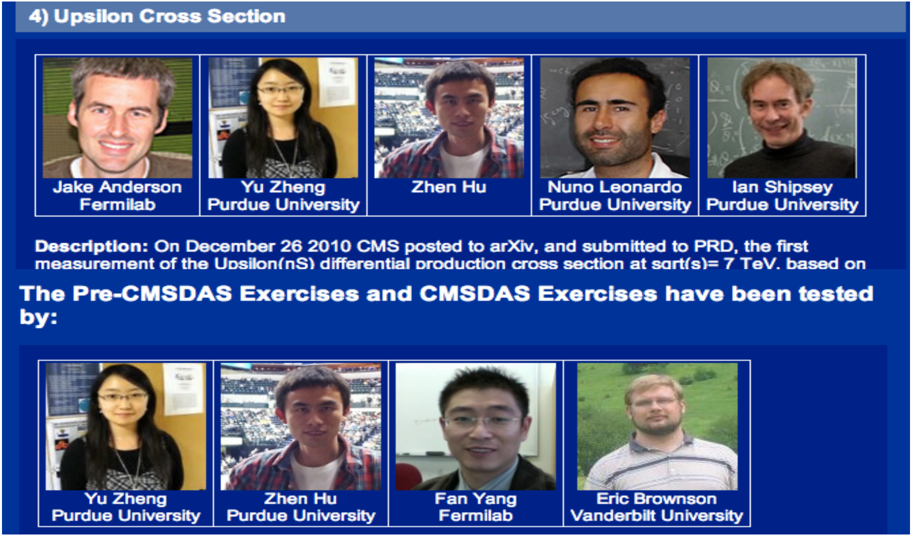
Service Work Contributed

- B-PAG trigger release validation contact



Service Work Contributed

- CMS Data Analysis School, facilitator, 2010-2012

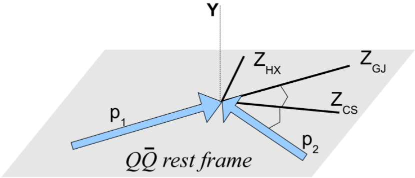


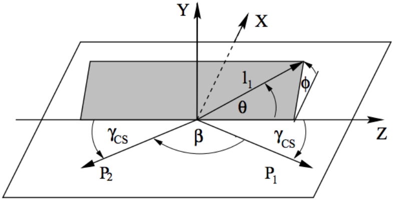
Thank you!

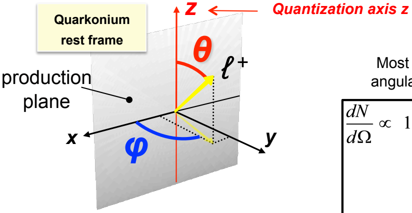
Back Up

Back Up

Polarization Frames



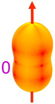




Most general observable
angular decay distribution:

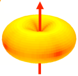
$$\frac{dN}{d\Omega} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_\varphi \sin^2\theta \cos 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi$$

$\lambda_\theta = +1$
$\lambda_\varphi = \lambda_{\theta\varphi} = 0$



$J_z = \pm 1$ $\rightarrow$ **λ_θ = +1** : **"transverse"** polarization

$\lambda_\theta = -1$
$\lambda_\varphi = \lambda_{\theta\varphi} = 0$



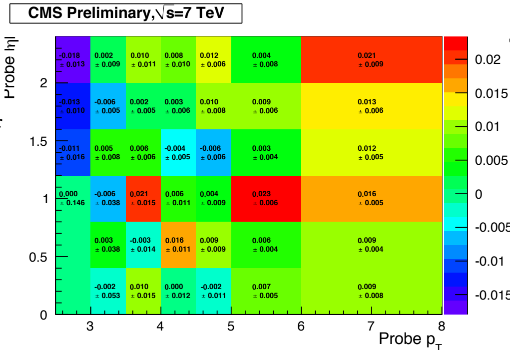
$J_z = 0$ $\rightarrow$ **λ_θ = -1** : **"longitudinal"** pol.

Trigger Efficiencies Bias

- A small bias on the probe sample may arise due to presence of second leg of Mu-plus-Track trigger.
- To estimate the bias: we made comparisons of the L3/L2 efficiency using different Tag requirements

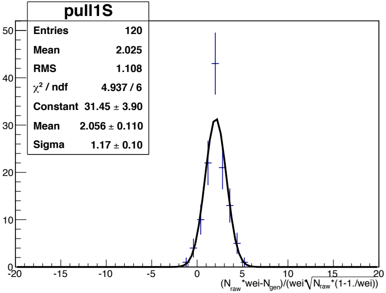
- Tag:
  - match to the Mu-plus-Track trigger object: bias L3/L2 eff
  - match to the Mu5L2Mu0 trigger object: unbias L3/L2 eff
- Probe: Tracker muons that matched to L2DoubleMu0 trigger object
- Passing Probe: Probes that matched to HLT_DoubleMu0 trigger object

$$\epsilon_{bias}(L3/L2) - \epsilon_{unbias}(L3/L2)$$



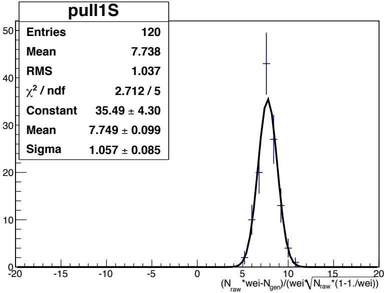
Monte Carlo Closure Test

Acceptance, Tracking, Track Quality, MC truth Single Muon Efficiencies Product (Υ sample)



- A biased pull, with a shifted mean at 2.06
- Factorization Hypothesis

Acceptance, Tracking, Track Quality, MC truth Single Muon Efficiencies Product (J/Ψ sample)

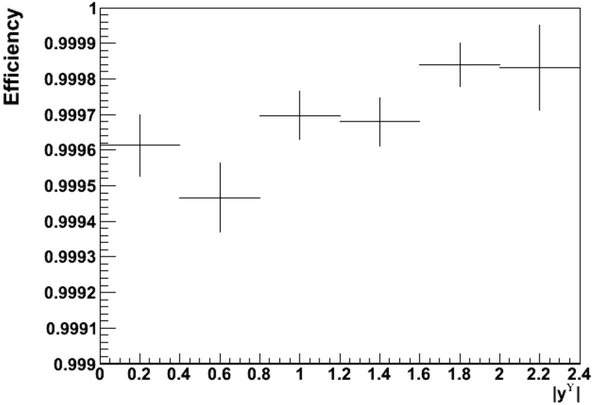


- A biased pull, with a shifted mean at 7.75
- Bias from applying J/Ψ muon efficiencies to Υ

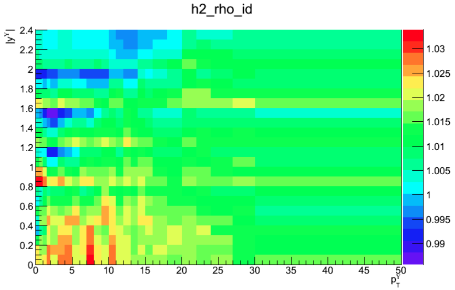
We need to introduce a correction factor.

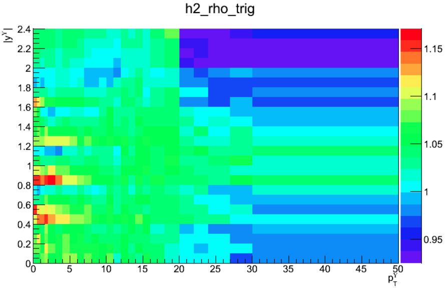
Other Efficiencies

- Vertex Probability > 0.001: 0.9916+/-0.0009
- When multiple candidates are found, choose the one with highest vertex probability: 0.9991+/-0.0009
- Track Quality Cuts: 0.9866 +/- 0.0005



Break down the ρ factor



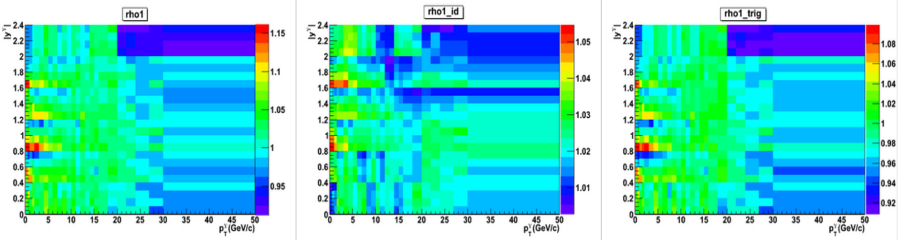


Break down the ρ factor

rho1 = e_(Y) / e_mu+(Y) * e_mu-(Y) (all efficiencies from MC truth matching)

rho1 reflects the effect coming from the factorization hypothesis

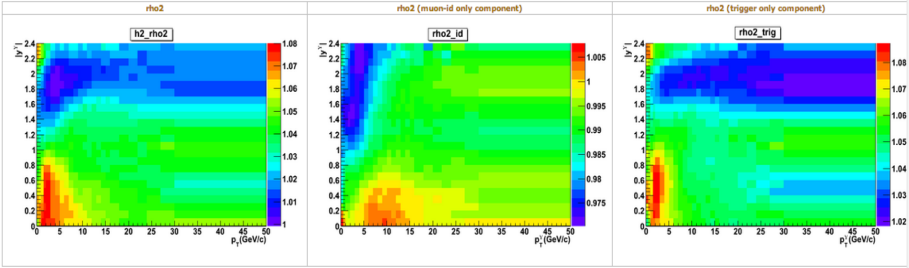
rho1	rho1 (muon-id only component)	rho1 (trigger only component)



Break down the ρ factor

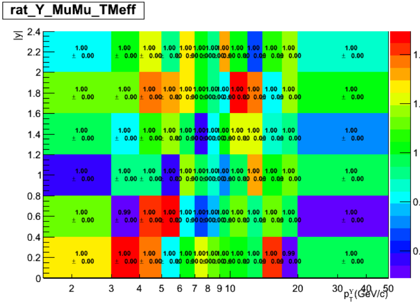
rho2 = [e_mu+(Y) * e_mu-(Y)] / [e_mu+(J/Psi) * e_mu-(J/Psi)]   (e_mu(Y)efficiencies from MC truth matching, e_mu(J/Psi) from MC TnP)

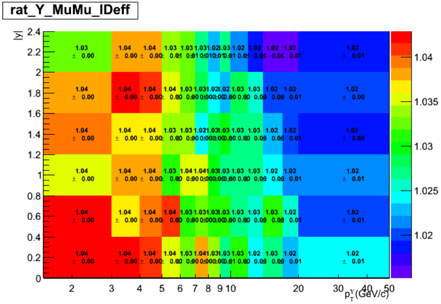
rho2 reflects the effect coming from using JPsi samples to measure muon efficiencies for Y and the intrinsic difference between tag and probe efficiencies and mc truth efficiencies (*could separate more)

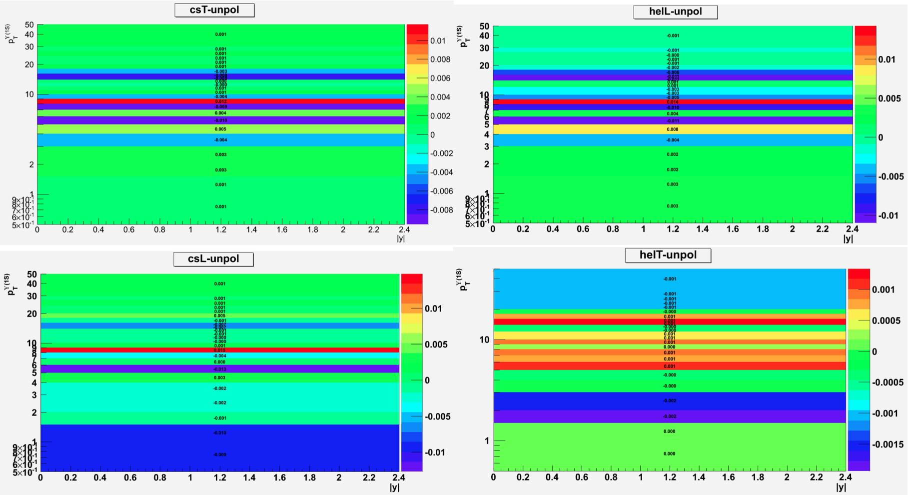


$$\epsilon(\Upsilon) = \epsilon(\mu^1_\Upsilon) \cdot \epsilon(\mu^2_\Upsilon) \cdot \rho' \tag{11}$$

- $\epsilon(\Upsilon)$: Monte Carlo Truth Dimuon (Υ) Efficiency
- $\epsilon(\mu^i_\Upsilon)$: Monte Carlo truth Single Muon Efficiency







Negligible effect.

Systematics

$\Upsilon(1S)\ |\mathbf{y}^{\Upsilon}| < \mathbf{2.4}$

p_T	A	S_p	A_{p_T}	A_{fsr}	ε_{muid}	ε_{trig}	ε_{ρ}	ε_{func}	ε_{trk}	PDF_{CB}	PDF_{bkgd}	M_{scale}
0.0 – 50.0	0.8 (0.8)	0.3 (0.3)	0.1	0.5	3.1 (2.0)	3.4 (3.4)	6.8	1.8	0.4 (0.3)	1.7	0.6	0.0 (0.0)
0.0 – 0.5	0.7 (0.8)	0.0 (0.1)	0.2	0.8	4.2 (3.2)	5.6 (4.9)	7.4	0.4	0.4 (0.3)	2.0	0.7	0.1 (0.1)
0.5 – 1.0	0.8 (0.8)	0.1 (0.1)	0.2	0.8	3.2 (3.2)	5.3 (4.6)	8.3	0.7	0.3 (0.4)	1.8	1.3	0.0 (0.4)
1.0 – 1.5	0.8 (0.8)	0.3 (0.2)	0.2	0.5	2.8 (3.5)	4.9 (4.7)	7.3	3.7	0.4 (0.4)	2.1	0.5	0.0 (0.0)
1.5 – 2.0	0.9 (0.8)	0.3 (0.3)	0.2	0.4	5.2 (2.7)	4.5 (4.5)	7.8	3.3	0.3 (0.3)	1.2	2.7	0.1 (0.0)
2.0 – 3.0	0.7 (0.7)	0.7 (0.7)	0.2	0.7	3.4 (2.4)	5.0 (8.5)	7.2	2.6	0.4 (0.3)	1.7	2.5	0.0 (0.0)
3.0 – 4.0	0.8 (0.8)	0.5 (0.6)	0.1	0.6	3.2 (1.9)	4.4 (3.8)	7.1	1.9	0.3 (0.4)	2.0	1.2	0.1 (0.1)
4.0 – 5.0	0.9 (0.7)	0.1 (1.1)	0.0	0.8	3.0 (1.8)	3.6 (3.6)	7.5	2.6	0.4 (0.6)	1.5	0.4	0.0 (0.2)
5.0 – 6.0	1.0 (0.8)	0.3 (0.2)	0.0	0.3	3.0 (1.7)	3.8 (7.3)	6.7	2.2	0.3 (0.4)	1.3	1.8	0.2 (0.2)
6.0 – 7.0	0.9 (0.9)	0.2 (0.2)	0.2	0.4	2.9 (1.8)	3.6 (3.1)	6.8	1.9	0.4 (0.2)	1.3	0.6	0.3 (0.3)
7.0 – 8.0	0.8 (0.8)	0.1 (0.1)	0.2	0.3	2.9 (1.8)	3.2 (2.8)	5.3	1.4	0.4 (0.4)	1.5	0.9	0.2 (0.2)
8.0 – 9.0	1.7 (1.7)	0.0 (0.0)	0.2	0.3	2.9 (1.8)	2.9 (2.6)	4.4	1.2	0.4 (0.4)	1.4	1.0	0.0 (0.0)
9.0 – 10.0	0.7 (1.0)	0.0 (0.1)	0.1	0.2	2.9 (2.0)	2.8 (2.5)	3.9	0.1	0.4 (0.4)	1.3	1.3	0.2 (0.1)
10.0 – 11.0	0.7 (0.6)	0.1 (0.1)	0.2	0.2	2.8 (1.9)	2.6 (2.3)	5.0	0.5	0.4 (0.4)	1.2	1.2	0.2 (0.0)
11.0 – 12.0	0.7 (0.7)	0.1 (0.1)	0.1	0.1	2.9 (2.0)	2.4 (2.1)	1.8	0.5	0.4 (0.4)	0.7	2.4	0.2 (0.2)
12.0 – 13.0	0.6 (0.6)	0.1 (0.1)	0.1	0.0	2.9 (2.1)	2.4 (2.1)	5.1	0.4	0.4 (0.4)	1.2	1.1	0.6 (0.6)
13.0 – 14.0	0.6 (0.6)	0.7 (0.7)	0.1	0.0	2.4 (2.6)	1.7 (2.5)	5.2	0.2	0.3 (0.3)	1.2	0.1	0.1 (1.0)
14.0 – 15.0	0.6 (0.6)	0.2 (0.1)	0.1	0.1	2.9 (2.2)	2.3 (2.1)	6.4	0.7	0.4 (0.3)	1.3	0.1	1.2 (0.4)
15.0 – 16.0	0.5 (0.5)	0.2 (0.3)	0.1	0.0	3.0 (2.3)	2.1 (1.9)	5.8	1.3	0.4 (0.3)	1.2	0.1	0.8 (0.1)
16.0 – 18.0	0.5 (0.4)	0.2 (0.1)	0.1	0.1	2.9 (2.2)	1.9 (1.7)	6.1	1.5	0.3 (0.3)	1.1	0.7	0.1 (0.4)
18.0 – 20.0	0.5 (0.5)	0.2 (0.2)	0.1	0.1	2.9 (2.2)	1.8 (1.6)	5.6	1.4	0.4 (0.3)	1.4	0.2	0.2 (0.2)
20.0 – 22.0	0.4 (0.4)	0.2 (0.2)	0.1	0.0	3.0 (2.4)	1.8 (1.6)	3.0	2.2	0.3 (0.3)	0.9	0.6	0.0 (0.0)
22.0 – 25.0	0.4 (0.5)	0.2 (0.2)	0.0	0.0	3.1 (2.5)	1.6 (1.5)	2.7	2.1	0.4 (0.3)	1.5	1.3	0.4 (0.4)
25.0 – 30.0	0.5 (0.5)	0.2 (0.2)	0.0	0.7	3.1 (2.7)	1.7 (1.5)	1.1	2.3	0.4 (0.4)	1.3	0.5	0.3 (0.2)
30.0 – 50.0	0.3 (0.3)	0.2 (0.2)	0.0	0.3	2.7 (2.2)	1.8 (1.6)	4.5	2.1	0.3 (0.3)	1.2	3.8	0.1 (1.0)

Tag and Probe utilizing Z resonance